

Searching for Particle Physics Beyond the Standard Model at the LHC and Elsewhere

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Abstract. Following a general introduction to open questions beyond the Standard Model, the prospects for addressing them in the new era opened up by the LHC are reviewed. Sample highlights are given of ways in which the LHC is already probing beyond previous experiments, including the searches for supersymmetry, quark and gluon substructure and microscopic black holes.

CERN-PH-TH/2011-003, KCL-PH-TH/2011-05

Keywords: Higgs boson, supersymmetry, dark matter, LHC
PACS: 12.10.-g, 12.60.Jv, 14.80.Bn, 14.80.Ly, 95.35.+d

INTRODUCTION

Particle physics is poised at the threshold of a new era. The Standard Model is well established, and poses a number of well-defined questions to be addressed by forthcoming experiments. The Large Hadron Collider (LHC) has now entered into operation with a centre-of-mass energy of 7 TeV, and is already surpassing previous accelerators in some of its probes of possible physics beyond the Standard Model. In the near future, the LHC will explore new physics at the TeV scale, where the mythical Higgs boson (or whatever replaces it) should lurk, and may also be able to identify particles providing the astrophysical dark matter. In parallel, other experiments complement and compete with the LHC, e.g., the Fermilab Tevatron collider and direct searches for dark matter. One way or another, many of the open questions beyond the Standard Model may soon be answered.

SETTING THE SCENE

The Standard Model rules OK

The matter particles of the Standard Model [1] comprise six quarks, and three charged leptons each accompanied by its light neutrino. Four fundamental forces act on these matter particles, namely gravity, electromagnetism and the strong and weak interactions. With the exception of gravity, each of these forces is known to have a quantum carrier particle, the photon, gluon, W^\pm and Z^0 particles, respectively. Taken together, these matter and force particles, their masses and couplings, are sufficient to describe the results of all confirmed laboratory experiments within their measurement accuracies. Examples

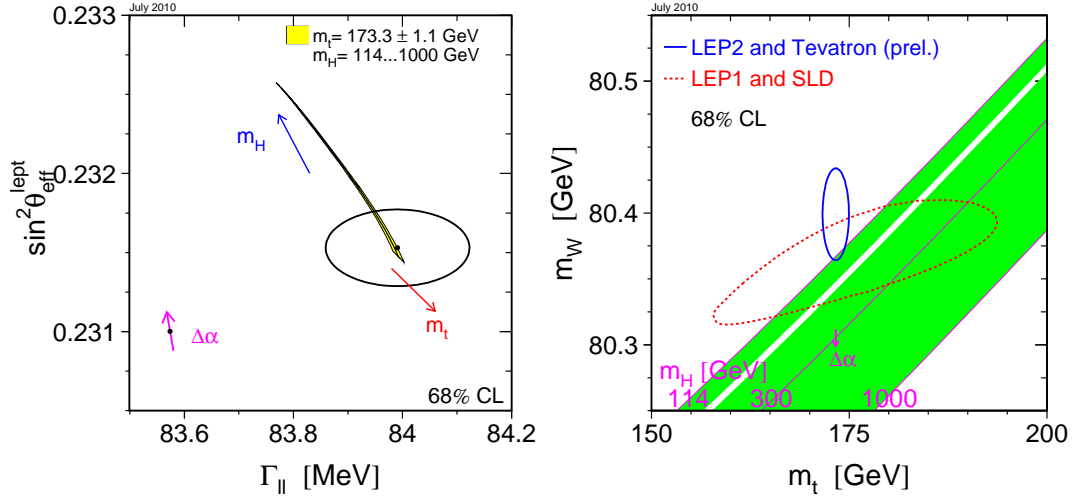


FIGURE 1. Precision measurements of (left) lepton couplings to the Z^0 and (right) m_W and m_t (solid ellipses), both of which favour a relatively low mass for the Higgs boson within the Standard Model [2]. In the right panel, the predictions for m_t and m_W based on low-energy measurements are shown as a mango-shaped dotted line.

of some high-precision measurements providing checks on Standard Model predictions for the weak and electromagnetic forces are shown in Fig. 1 [2]. Measurements of the Z^0 couplings to charged leptons, shown in the left panel, agree with the Standard Model prediction at the *per mille* level, and are sensitive *via* quantum effects to the masses of the top quark and the hypothetical Higgs boson. Measurements of the masses of the top quark and W^\pm boson also agree very well with Standard Model predictions based on lower-energy data, as shown in the right panel. Interestingly, both sets of measurements seem to favour a relatively low mass for the unseen Higgs boson, as do a number of other precision electroweak measurements.

These and many other successes inform us that the Standard Model particles can be regarded as the cosmic DNA, encoding the information required to assemble all the visible matter in the Universe.

Questions beyond the Standard Model

Many of the important open questions beyond the Standard Model are already implicit in its successes [1]. First and foremost may be *the origin of particle masses*: are they indeed linked to a Higgs boson, or has Nature chosen a different mechanism? As has already been mentioned, there are six quarks, three charged leptons and three neutrinos: *why are there so many types of matter particles*, and why not either more or fewer? The Standard Model describes very well the visible matter in the Universe, but *what is the dark matter* in the Universe, and is it composed of elementary particles? There

are several different fundamental forces, and the electromagnetic and weak forces are partially unified: *is it possible to unify* all the fundamental forces? Finally, theoretical physicists should be deeply embarrassed that, about a century after the discovery of quantum mechanics and general relativity, we still do not have an established, *consistent quantum theory of gravity*. Maybe it could be based on string?

Each of these questions is being addressed by the LHC, which may well provide some of the answers. For example, the search for a Standard Model Higgs boson has been a benchmark in the design of the ATLAS and CMS detectors for the LHC [3], which should either discover or exclude it over all the mass range up to ~ 1 TeV. A dedicated experiment, LHCb, is studying CP violation and rare decays of heavy quarks, looking for new physics beyond the dominant Cabibbo-Kobayashi-Maskawa paradigm within the Standard Model [4]. Supersymmetry and/or extra dimensions are features of unified theories, and may also lie within the reach of the ATLAS and CMS experiments at the LHC [3]. Last but not least, detailed measurements in such theories might provide vital clues towards the construction of a unified quantum Theory of Everything, and the AdS/CFT correspondence suggested by string theory may provide insights into the heavy-ion collisions being studied by ALICE [5], ATLAS and CMS.

Of course, the LHC is not the only location for experiments addressing these questions, and some other experimental approaches are also featured in this talk.

TO HIGGS OR NOT TO HIGGS?

Newton taught us that weight is proportional to mass, and Einstein discovered that energy is related to mass, but neither of these honourable gentlemen got around to explaining the origin of mass. So where do particle masses come from? Did Englert, Brout [6] and Higgs [7] find the answer? Are they due to the mythical Higgs boson, which has now become the particle physicists' Holy Grail?

A Flaky Higgs Analogy

For a simple analogue of the Englert-Brout-Higgs [6, 7, 8] mechanism and the role of the Higgs boson, think about an infinite, flat, featureless, homogeneous and isotropic field of snow, like the Arctic tundra in winter. Now consider trying to cross it. If you have skis, you will not sink into (interact with) the Englert-Brout-Higgs snow field, and will move fast, like a particle without mass such as the photon, which always travels at the speed of light. On the other hand, if you have snowshoes, you will sink into the snow (interact with the Englert-Brout-Higgs field), and move more slowly, rather like a particle with mass such as the electron. Finally, if you have no snow equipment apart from hiking boots, you will sink deeply into (interact strongly with) the Englert-Brout-Higgs snow field, like a particle with large mass such as the top quark.

So where does the Higgs boson fit into this analogy? Just as a real snow field is made of snowflakes, and the electromagnetic field has an associated quantum (the photon), there should be a quantum of the Englert-Brout-Higgs field, as was first pointed out explicitly by Higgs [7]. This snowflake is what we call the Higgs boson. In the original

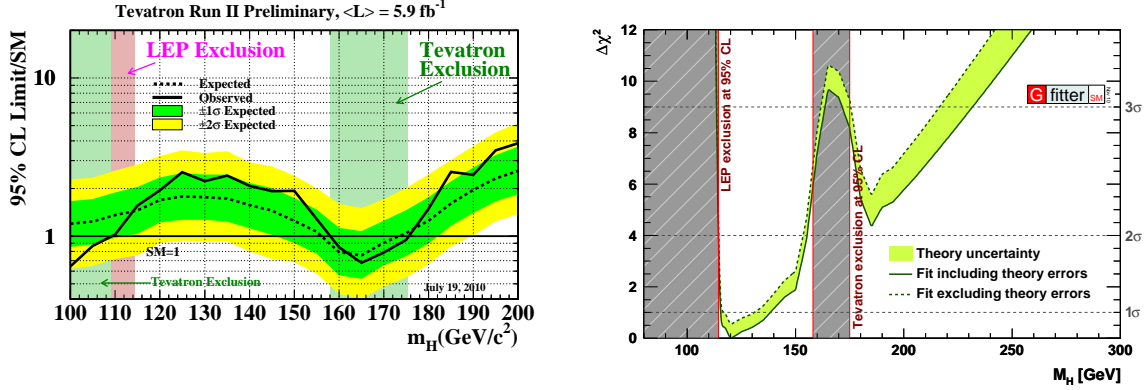


FIGURE 2. Searches for the Standard Model Higgs boson at the Tevatron (left) exclude the range $158 \text{ GeV} < m_H < 175 \text{ GeV}$ [10]. Combining the Tevatron search with the LEP search [9] and the precision electroweak data[2], one obtains (right) the global χ^2 function that favours $m_H \sim 120 \text{ GeV}$ [11].

model of Englert, Brout and Higgs the field and the quantum are elementary, but real life may be more complicated: just as every snowflake is a different composite object made out of more elementary ice crystals, there may be many different Higgs bosons, and they may be composite objects made out of constituents that are more elementary.

How Heavy is the Higgs Snowflake?

The direct search for the Standard Model Higgs boson at LEP established the lower limit [9]:

$$m_H > 114.4 \text{ GeV}. \quad (1)$$

Moreover, as we saw in Fig. 1, the precision electroweak data are sensitive to both m_t and m_H . Incorporating the current experimental value $m_t = 173.1 \pm 1.3 \text{ GeV}$, the best-fit value and 68% confidence-level range for the Higgs mass are [2]:

$$m_H = 89^{+35}_{-26} \text{ GeV}. \quad (2)$$

The corresponding 95% confidence-level upper limit is $m_H < 158 \text{ GeV}$, or 185 GeV if the direct limit (1) is included.

The direct experimental search for the Higgs boson is currently being led by the Fermilab Tevatron, which has recently excluded the range [10]:

$$158 \text{ GeV} < m_H < 175 \text{ GeV}, \quad (3)$$

as seen in the left panel of Fig. 2. The right panel displays the result of a combined χ^2 analysis of the precision data with the direct searches at LEP and the Tevatron. We see that the most likely value of the Higgs mass is $m_H \sim 120 \text{ GeV}$ [11].

DARK MATTER

Astrophysicists and cosmologists tell us that there is five to ten times as much invisible dark matter as the visible stuff out of which galaxies, stars, planets and people are made [12]. The presence of this dark matter is felt gravitationally by visible matter, whose velocities inside galaxies and clusters are much larger on average than would be expected on the basis of the virial theorem and the density of the visible matter itself. The galaxies and clusters need additional dark matter to keep them together, which might well be made out of massive neutral particles. If these were once in thermal equilibrium with the visible matter in the early Universe, one expects them to weigh less than about a TeV each, putting them within reach of the LHC. There are many candidates in composite models, theories with extra dimensions, etc., but here we concentrate on the lightest supersymmetric particle (LSP) [13] as a prototype benchmark scenario, mentioning some others.

WHY I LOVE SUSY

Supersymmetry (SUSY) is the only symmetry that could unify matter particles and force particles. This is because it is unique in being able to relate particles spinning at different rates, such as the spin-0 Higgs boson, spin- $\frac{1}{2}$ matter particles such as the electron and quarks, spin-1 intermediate bosons such as the photon, the spin- $\frac{3}{2}$ supersymmetric partner of the graviton, called the gravitino, and the spin-2 graviton itself [14]. In addition, it would help fix particle masses [15] and unify the fundamental forces [16] and it predicts that the Higgs boson should be relatively light [17], as indicated by the precision electroweak data, as well as potentially providing the dark matter [13] postulated by the astrophysicists and cosmologists.

To see how SUSY could help the Higgs boson fix particle masses [15], consider loop corrections to the squared mass of the Higgs boson. Generic one-loop fermion and boson loops in the Standard Model are each quadratically divergent, being $\propto \int^\Lambda d^4k/k^2$ where Λ is a cut-off in momentum space, representing the maximum energy scale up to which the Standard Model remains valid:

$$\begin{aligned}\Delta m_H^2 &= -\frac{y_f^2}{16\pi^2} \left[2\Lambda^2 + 6m_f^2 \ln \left(\frac{\Lambda}{m_f} \right) \right], \\ \Delta m_H^2 &= \frac{\lambda_s}{16\pi^2} \left[\Lambda^2 - 2m_s^2 \ln \left(\frac{\Lambda}{m_s} \right) \right].\end{aligned}\tag{4}$$

Here y_f denotes a Higgs-fermion-antifermion Yukawa coupling, and λ_s is a quartic scalar coupling. If Λ is of the same order as the grand unification or Planck scale, these loop corrections are individually much greater than the possible physical value of the Higgs mass. The presence of such quadratic divergences is *not* incompatible with a light elementary Higgs boson, but it would seem quite unnatural to obtain a light Higgs mass as the result of a cancellation between the very cut-off-sensitive loop diagrams and a tree-level input contribution of the opposite sign. However, it is apparent that, since the

fermion and scalar diagrams have opposite signs, their quadratic divergences cancel if

$$\lambda_s = 2y_f^2. \quad (5)$$

Remarkably this is exactly the relation between fermion and scalar couplings that occurs in a supersymmetric theory, and the same relation cancels all quadratic (and some logarithmic) divergences in all orders of perturbation theory [18]. The residual logarithms are not too large numerically if Λ is of the same order as the grand unification or Planck scale, so SUSY restores the naturalness of a light Higgs boson in a theory with light supersymmetric partners of all the Standard Model particles. The supersymmetric particle mass scale effectively replaces the upper cut-off Λ on the validity of the Standard Model.

Indeed, SUSY actually *predicts* a light Higgs boson, typically $m_H < 130$ GeV in the minimal supersymmetric extension of the Standard Model [17].

The appearance of supersymmetric particles would change the evolution of the gauge couplings at larger energy-momentum scales. This is welcome, because extrapolation of the measured gauge coupling strengths to high energies using just the renormalization-group equations of the Standard Model reveals no energy at which they would all be equal, making conventional unification impossible. On the other hand, incorporating supersymmetric particles with masses ~ 1 TeV, as suggested by the above naturalness argument, could bring the gauge couplings together at some energy scale $\sim 10^{16}$ GeV, making possible unification of the fundamental interactions [16]. Further tests of unification would be made possible by measuring the masses of the different supersymmetric particles [19].

PARTICLE COSMOLOGY

The fact that the sky is dark at night tells us that the Universe cannot be in a strictly steady state, and its current expansion was discovered by Hubble, who first observed the redshifts in the light from other galaxies. The cosmic microwave background radiation, emitted when atoms were first formed, is evidence that the Universe was once about 1000 times hotter than it is today. The cosmological abundances of light elements agree reasonably well with calculations based on Big Bang nucleosynthesis (though see [20]), and take us back to when the Universe was about 10^9 times hotter than today. We believe that protons and neutrons were formed when the Universe was about 100 times hotter still, and the LHC has recently been colliding lead ions with energies of 2.76 GeV/nucleon in order to understand better the quark-gluon matter that filled the Universe before this epoch. Proton-proton collisions at the LHC recreate quark and gluon collisions at energies similar to those typical of the very early Universe when it was about 1000 times hotter still. We believe that this is the epoch when particle masses appeared through the Englert-Brout-Higgs mechanism, as described above.

At least two major cosmological mysteries may be resolved by the ability of LHC collisions to reach back to the very early Universe. In typical models, the dark matter particles decouple from visible particles some time between the epochs of mass generation and the transition from quark-gluon to hadronic matter. Additionally, it is possible,

e.g., in supersymmetric models, that the cosmological baryon asymmetry was generated around the epoch of mass generation, as discussed next.

THE CREATION OF MATTER

Following the postulation of antimatter by Dirac and its discovery in the cosmic rays, for over 30 years particle physicists thought that matter and antimatter particles were exactly equal and opposite, having identical masses and opposite electric charges. However, in 1964 an experiment revealed unexpectedly that some matter and antimatter particles actually decay slightly differently, violating the combination of charge conjugation and parity symmetries (CP), and also time-reversal symmetry (T). In 1967, Sakharov [21] pointed out that such a matter-antimatter asymmetry combined with a departure from thermal equilibrium during the expansion of the Universe could enable a difference between the cosmological abundances of matter and antimatter to be created. If such an excess of matter particles was created, around the epoch of the transition from quark-gluon matter to hadronic matter, all the particles of antimatter would have annihilated with matter particles, leaving a surplus of the latter to survive into the Universe today.

Then, in 1973 Kobayashi and Maskawa showed that CP and T violation could be accommodated in the Standard Model with six quarks, and this paradigm has been established by many subsequent experiments [22]. Could this mechanism be responsible for the creation of the matter in the Universe? Apparently not, because no strong breakdown of thermal equilibrium is expected to have occurred in the Standard Model, and the amount of Kobayashi-Maskawa CP violation seems inadequate.

However, many theories beyond the Standard Model, including SUSY, contain extra sources of CP violation and mechanisms for matter creation, and some of these could have created a matter-antimatter asymmetry at the epoch of the transition that generated particle masses [23]. Such theories are susceptible to experimental tests at the LHC, and one of its experiments, LHCb, is dedicated to the study of CP violation and rare B decays that might cast light on the creation of matter - though other realizations of Sakharov's idea would involve physics at earlier epochs beyond the direct reach of the LHC.

TOWARDS A THEORY OF EVERYTHING?

Unifying the fundamental interactions was Einstein's dream in his latter decades, and extra dimensions were among the ideas he explored. They also play essential roles in many contemporary scenarios for unification and quantum gravity, e.g., in the context of string theory. In fact, string theory seems to require both extra dimensions and SUSY, though our present understanding is insufficiently advanced to calculate the energy scales at which they might appear. In some scenarios with extra dimensions, gravity becomes strong at the TeV scale, and microscopic black holes might be fabricated in quark and gluon collisions at the LHC [24]. If so, their decays would provide wonderful laboratories for probing theories of quantum gravity, e.g., by measuring the grey-body factors of Hawking radiation into different particle species [25].

THE LHC PHYSICS HAYSTACK(S)

Why has the LHC not discovered anything yet? Cross sections for heavy particles typically scale as $1/M^2$, and many, e.g., the Higgs boson, have cross sections suppressed by powers of small couplings. For these reasons, their cross sections are much smaller than the total cross section, which is $\mathcal{O}(1/m_\pi^2) \sim 1/(100 \text{ MeV})^2$. Therefore, cross sections for new physics are typically a trillionth of the total cross section. Since many new particle signatures, e.g., for the Higgs boson, are accompanied by large backgrounds, many events may be needed to establish a signal. Looking for new physics at the LHC is like looking for a needle in $\sim 100,000$ haystacks! At the time of writing, the LHC experiments have each accumulated just a few trillion events, so it should not be surprising that they have not yet discovered new physics. Nevertheless, already the LHC has established some of the strongest limits on new physics, as discussed below, and the number of LHC collisions may increase by a factor ~ 100 in the coming year, putting it firmly in the discovery business.

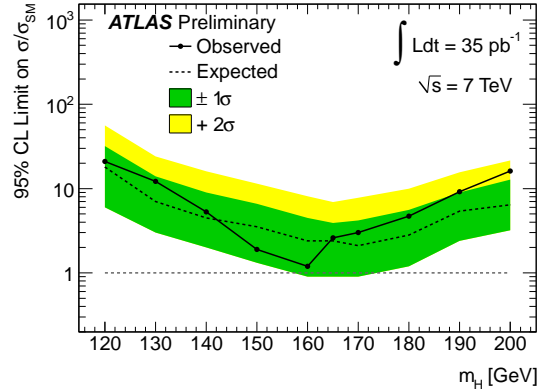


FIGURE 3. The result of an initial ATLAS search for the Higgs boson in the $H \rightarrow WW$ channel, showing the expected signal rate, relative to the SM rate, that is excluded at the 95% CL [26].

THE SEARCH FOR THE HIGGS BOSON

In the range of Higgs masses below 150 GeV, which currently seems the most plausible, several different Higgs production and decay modes may contribute to the search for the Higgs boson at the LHC, including $gg, W^+W^- \rightarrow H \rightarrow \gamma\gamma, \tau\tau, W^+W^-$ and $Z^0Z^{0*} \rightarrow 4$ leptons. The result of an initial ATLAS search for the Higgs boson are shown in Fig. 3: already with only 35/pb of data analyzed, the LHC upper limit on Higgs production approaches the Standard Model expectation and the Tevatron limit. The latest estimates by ATLAS [27] and CMS [28] of their likely future sensitivities to a Standard Model Higgs boson are shown in Fig. 4, for various assumptions about the available LHC integrated luminosity and centre-of-mass energy. It is now planned to extending the present run into 2011, operating at 7 TeV this year but maybe increasing the LHC energy to 8 TeV in 2012, which should provide good prospects of discovering (or excluding) a Standard Model Higgs boson at any mass up to ~ 600 GeV. In parallel,

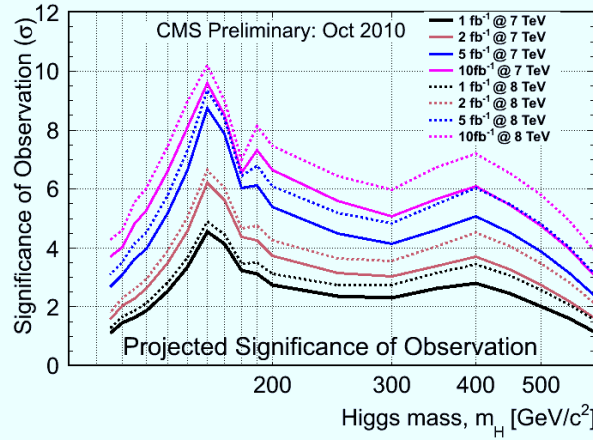
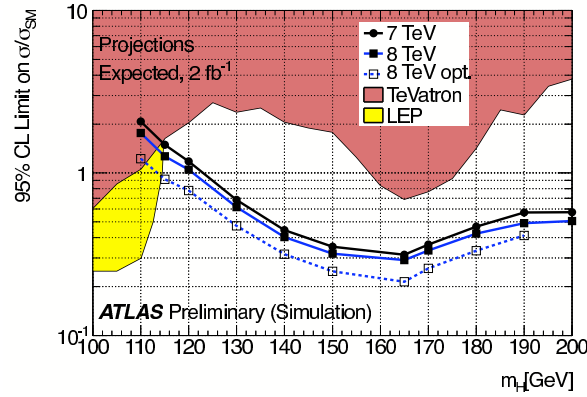


FIGURE 4. The expected sensitivities of the ATLAS (upper) and CMS (lower) experiments at the LHC for observing the Standard Model Higgs, as a function of the integrated luminosity and centre-of-mass energy [27, 28].

it had been proposed to extend the Tevatron run for three years, offering the prospect of discovering a light Higgs boson *via* complementary production and decay channels, such as $W + H, H \rightarrow \bar{b}b$, providing valuable additional science. Unfortunately, this proposal has not been accepted [29]. Nevertheless, the question of the origin of particle masses may soon be answered.

The stakes in the Higgs search are high. The answer to the mass question will tell us how the symmetry between different particles is broken, and whether there is an elementary scalar field - something which has never been seen and would surprise many theorists. The existence and mass of the Higgs boson will also foretell the fate of the Standard Model at high energies [30], thereby establishing the framework for possible unified theories. It will also tell us whether and how mass appeared when the Universe was a picosecond old, and may indicate whether the Higgs could have played a role in creating the matter in the Universe. The existence of a Higgs boson could have other cosmological implications. For example, many models of inflation postulate a similar

elementary scalar field (or even the Higgs field itself [31]) to explain the size and age of the Universe. Moreover, the Higgs has the potential to contribute $\sim 10^{60}$ times more dark energy than what is observed, and measurements of the Higgs boson may cast light on the problem of dark energy.

THE SEARCH FOR SUSY

Supersymmetric models

In the following we discuss the prospects for SUSY searches in the context of the minimal supersymmetric extension of the Standard Model (the MSSM), in which known particles are accompanied by spartners with spins differing by $\frac{1}{2}$, and there are two Higgs doublets, with a coupling μ , and v.e.v.'s in the ratio of $\tan\beta$. In addition, there are unknown parameters that characterize supersymmetry breaking, namely soft scalar masses m_0 , spin- $\frac{1}{2}$ gaugino masses $m_{1/2}$, trilinear soft supersymmetry-breaking couplings A_λ , and a bilinear soft coupling B_μ . The MSSM has over 100 parameters, too many for practical phenomenology until many more experimental constraints become available, e.g., from the LHC. In the mean time, it is often assumed that the scalar and gaugino masses are universal, and likewise the trilinear couplings. This is consistent with experimental data and measurements of rare flavour-changing processes, which suggest a super-GIM mechanism [32] as would be provided by universal m_0 parameters for the squarks and sleptons in different generations but with the same quantum numbers [33], and GUTS, which would link the m_0 parameters of squarks and sleptons in the same GUT multiplet and possibly also the $m_{1/2}$ parameters for the SU(3), SU(2) and U(1) gauginos. This is the simplified phenomenological framework known as the constrained MSSM (the CMSSM), which has just 4 variables and the sign of μ as parameters. Unfortunately, there is no strong motivation for it from fundamental theory such as strings, and one may consider alternatives.

Generalizing the CMSSM, one may note that none of the arguments in the previous paragraph give any reason why the soft supersymmetry-breaking contributions to the masses of the two Higgs doublets should be universal, and one may consider non-universal Higgs mass models in which they are either equal (the NUHM1) or unequal (the NUHM2). Alternatively, one may consider more constrained models, such as minimal supergravity (mSUGRA), which fixes the gravitino: $m_{3/2} = m_0$ and imposes the relation $B_\mu = A_\lambda - m_0$. One may also consider an intermediate, very constrained model (the VCMSSM) in which the relation $B_\mu = A_\lambda - m_0$ is retained but the gravitino mass relation is dropped. In the following, we will compare the prospects for SUSY searches in the CMSSM, NUHM1, VCMSSM and mSUGRA.

Candidates for dark matter

Many supersymmetric models have a multiplicatively-conserved R -parity: $R = (-1)^{2S-L+3B}$, where S, L and B denote the spin, lepton and baryon numbers, respectively [34]. In such models, heavier sparticles are condemned to be produced in

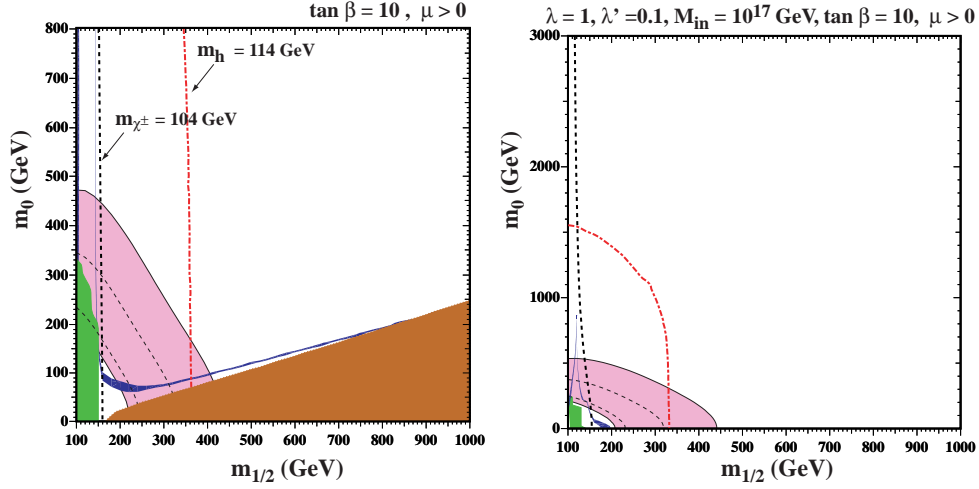


FIGURE 5. The $(m_{1/2}, m_0)$ planes for the CMSSM with $\tan\beta = 10$ and $\mu > 0$ assuming (left) universality at the grand unification scale $\sim 10^{16}$ GeV [37] and (right) assuming universality at 10^{17} GeV [38]. The near-vertical (red) dot-dashed lines are the contours $m_h = 114$ GeV [9], and the near-vertical (black) dashed line is the contour $m_{\chi^\pm} = 104$ GeV [39]. The medium (dark green) shaded region is excluded by $b \rightarrow s\gamma$, and the dark (blue) shaded areas make up the region favoured by determinations of the cosmological dark matter density [40]. The dark (brick red) shaded region is excluded because there the LSP would be the charged lighter stau slepton. The region favoured by the E821 measurement of $g_\mu - 2$ at the 2- σ level, is shaded (pink) and bounded by solid black lines, with dashed lines indicating the 1- σ ranges [41].

pairs and to decay into lighter ones, so as to conserve R -parity, and the lightest sparticle (LSP) is stable, as it has no allowed decay mode. Hence, it could lurk around today as a relic from the Big Bang, and constitute the dark matter. Other models such as scenarios with universal extra dimensions and composite models may have analogous dark matter candidates, the LKP [35] and LTP [36], respectively, that are benchmarked by discussing the LSP.

The LSP (LKP, LTP) cannot be charged or have strong interactions, as otherwise it would bind to conventional particles forming anomalous heavy ‘nuclei’ that have not been seen. *A priori*, weakly-interacting LSP (LKP) candidates in the MSSM (universal extra dimension scenario) include the supersymmetric partner (Kaluza-Klein excitation) of either (i) some neutrino $\tilde{\nu}$ (V_{KK}), or (ii) a mixture of the neutral SU(2) and U(1) gauginos and Higgs bosons, namely the lightest neutralino χ (V_{KK}), or (iii) the gravitino. In the supersymmetric framework, the $\tilde{\nu}$ is apparently excluded by a combination of LEP data and direct searches for astrophysical dark matter, and in the following we focus on the lightest neutralino χ [13], whilst recognizing that the gravitino is also a valid possibility that would have distinctive signatures at the LHC but be very difficult to detect in any astrophysical context.

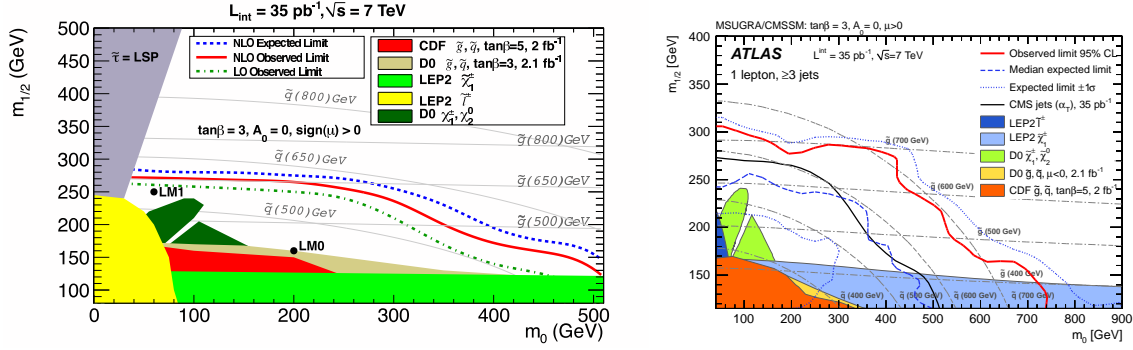


FIGURE 6. The exclusions in the $(m_0, m_{1/2})$ plane from (left) the initial CMS search for jets + missing transverse energy events with 35/pb of analyzed data at 7 TeV in the centre of mass [44], and (right) the initial ATLAS search for lepton + jets + missing transverse energy events [45].

Constraints on SUSY

The classic collider signature for any dark matter candidate is missing transverse momentum, as inferred from an imbalance in the transverse energy, and in the neutralino LSP scenario the absence of such a signature at LEP and the Tevatron collider implies that most sparticles must weigh > 100 GeV and squarks and gluinos must weigh > 400 GeV. The absence of the Higgs boson at LEP and the consistency of B decays such as $b \rightarrow s\gamma$ and $B_s \rightarrow \mu^+\mu^-$ also impose important constraints on SUSY. The most tangible positive indication for SUSY is the cosmological density of dark matter. Since the density is known with a precision of a few percent [40], so also is some combination of SUSY model parameters in any given scenario. The left panel of Fig. 5 shows a compilation of constraints in the $(m_{1/2}, m_0)$ plane for the CMSSM with $\mu > 0$ and $\tan\beta = 10$, assuming that the dark matter is composed of neutralinos χ and that the universality of the CMSSM applies at an input grand unification scale $\sim 10^{16}$ GeV [37]. In addition to the phenomenological constraints mentioned above, this figure also shows the region of parameter space excluded because the LSP is charged. Finally, also displayed is the region that would be favoured if one interprets the apparent discrepancy between experiment [41] and the Standard Model calculation of the anomalous magnetic moment of the muon, $g_\mu - 2$, as being due to SUSY. The validity of this interpretation is still contested [42], so we also discuss below the implications of dropping it. The right panel of Fig. 5 shows a similar compilation of constraints in the $(m_{1/2}, m_0)$ plane, this time assuming that the universality of the CMSSM applies at an input scale of 10^{17} GeV [38], revealing a rather different picture! In the following, we assume CMSSM universality at the grand unification scale.

Global supersymmetric fits

We now present some results from frequentist supersymmetric fits to the parameters of the CMSSM, NUHM1, VCMSSM and mSUGRA [43], incorporating contributions

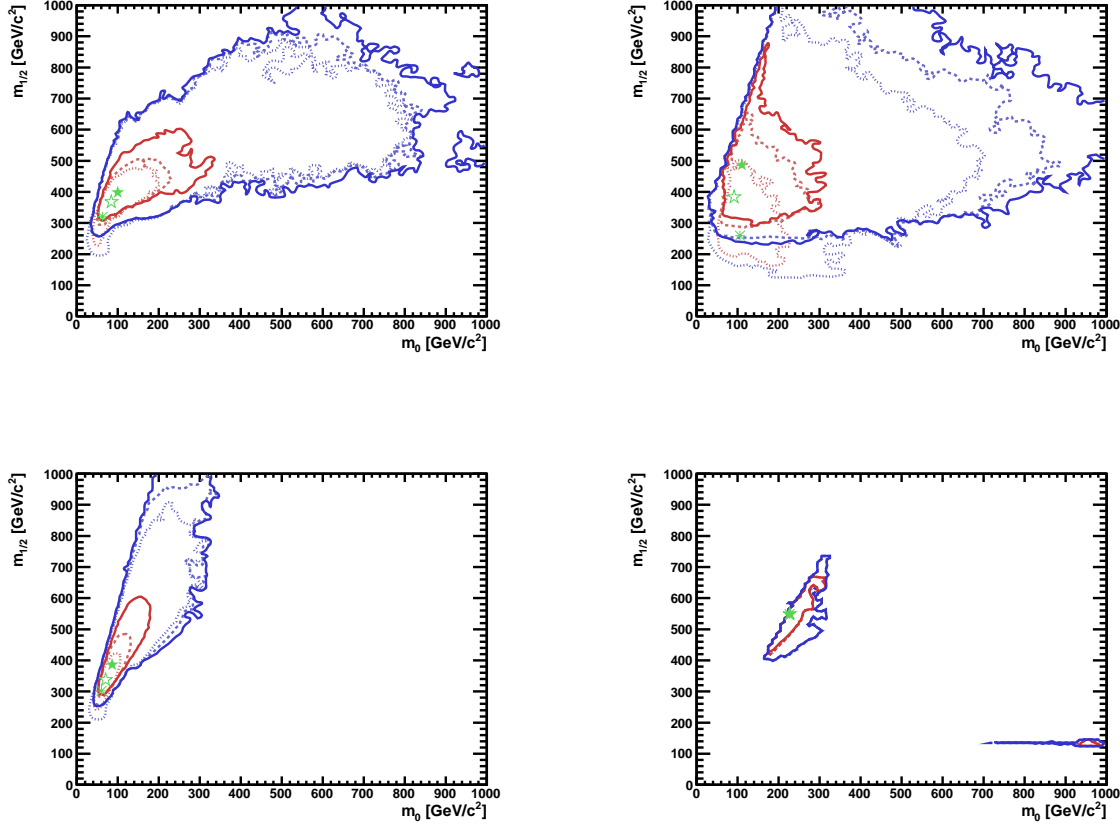


FIGURE 7. The $(m_0, m_{1/2})$ planes in the CMSSM (upper left), NUHM1 (top right), VCMSSM (lower left) and mSUGRA (lower right). In each panel, we show the 68 and 95% CL contours (red and blue, respectively) found in a frequentist analysis of the available constraints [43, 46], both before applying the LHC constraints (dotted lines) and after applying the CMS [44] constraint (dashed line) and the ATLAS constraint [45] (solid line). Also shown as (green) snowflakes, open and full stars are the best-fit points in each model.

from all the above constraints to total likelihood function, also including the constraints provided by the initial LHC searches for SUSY reported in [44, 45] shown in Fig. 6, as discussed in [46].

Fig. 7 displays the $(m_0, m_{1/2})$ planes for these models, showing the best-fit points as well as the regions favoured at the 68 and 95% CL. The differences between the dotted, dashed and solid lines illustrate the impact of the initial LHC constraints from the CMS and ATLAS Collaborations shown in the left and right panels of Fig. 6 [44, 45], respectively, in which no significant excess of SUSY-like events were reported.

Comparing with the expected reaches for SUSY detection at the LHC [47, 48], there should be good prospects for discovering SUSY in the near future. It should be stressed, however, that these conclusions depend quite critically on the $g_\mu - 2$ constraint: as seen in Fig. 8 for the CMSSM case before applying the LHC constraints, the other data show only a slight preference for light sparticles, e.g., *via* the measurement of m_W

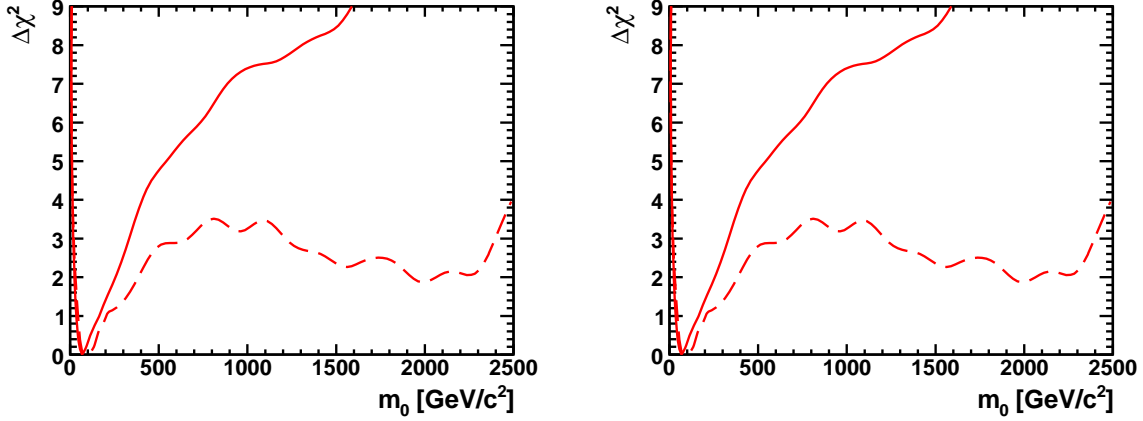


FIGURE 8. The likelihood functions for m_0 in (left) the CMSSM and (right) the NUHM1. The χ^2 values including (excluding) the $g_\mu - 2$ constraint are shown as the solid (dashed) curves [49].

shown in the right panel of Fig. 1. The single-variable χ^2 for some particle masses and other observables are shown in Fig. 9. We note that the gluino is expected to weigh < 1.5 TeV in all these models, potentially within the reach of the LHC in 2011/12, that the Higgs boson is predicted to weigh between 115 and 120 GeV (the curves shown have a theoretical uncertainty estimated at ± 3 GeV), and that $B_s \rightarrow \mu^+ \mu^-$ decay may occur at a rate measurably different from the Standard Model prediction, particularly in the NUHM1. LHCb may attain sensitivity close to this prediction also in 2011/12.

Searches for SUSY dark matter

Several searches to search for supersymmetric dark matter have been proposed, principally with the lightest neutralino χ in mind. These include searches for $\chi\chi$ annihilations in the galactic halo into antiprotons, positrons, etc., that could be detected among the cosmic rays. Another possibility is to look for annihilations into γ rays in the galactic centre. A third possibility is to look for annihilations into energetic neutrinos in the core of the Sun or Earth. Most promising may be to search directly for χ scattering on nuclei in the laboratory.

As seen in the lower right panel of Fig. 9, the cross section for spin-independent dark matter scattering on a proton may be $\sim 10^{-45}$ cm² [46], within an order of magnitude of the present experimental limit, and within reach of experiments now running or in preparation. These experiments may provide the keenest competition for the LHC in the search for supersymmetric particles. Note, however, that the two classes of experiment are quite complementary. The LHC experiments may be able to discover missing-energy events and show that they are due to the production and decay of sparticles, but they will not be able to prove that the particles carrying away the missing energy are completely stable and constitute the dark matter. On the other hand, direct dark matter searches would be unable to prove that any detected dark matter particle was supersymmetric.

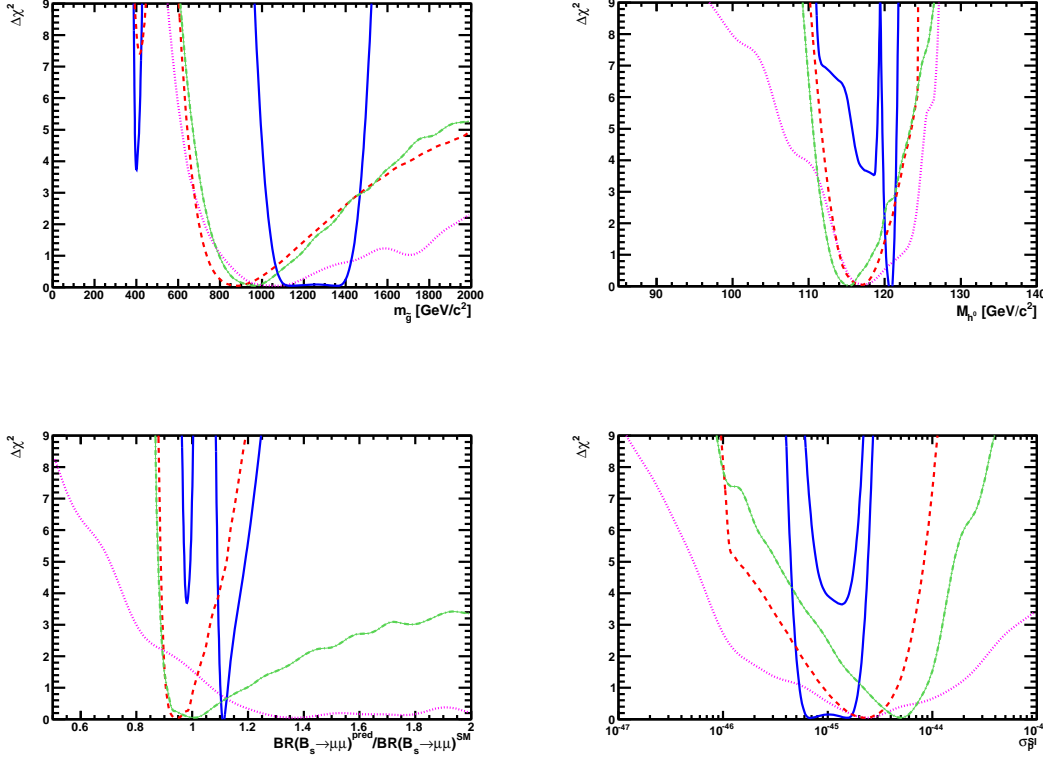


FIGURE 9. The likelihood functions for (upper left) $m_{\tilde{g}}$, (upper right) m_H (lower left) $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$ and (lower right) the spin-independent $\chi - p$ scattering cross section for the CMSSM (green dash-dotted lines), the NUHM1 (purple dotted lines), the VCMSSM (red dashed lines), and mSUGRA (blue solid lines) [49, 43, 46].

Only the combination of the two classes of experiment would be able to establish a complete picture of SUSY, and the same is true in other scenarios for dark matter.

THE LHC ROULETTE WHEEL

The LHC is unique in my experience in that it is opening up the exploration of a new energy range up to a few TeV where there are good reasons to expect new physics associated with the origin of particle masses and dark matter, but we do not know what form this new physics may take: Higgs, SUSY or something else. One can compare the LHC start-up to a game of roulette: the wheel is now turning, the theoretical '*jeux sont faits*', and it just remains to see where the ball will stop. The LHC has already told us about a few places where the ball does not stop, as described in the following paragraphs.

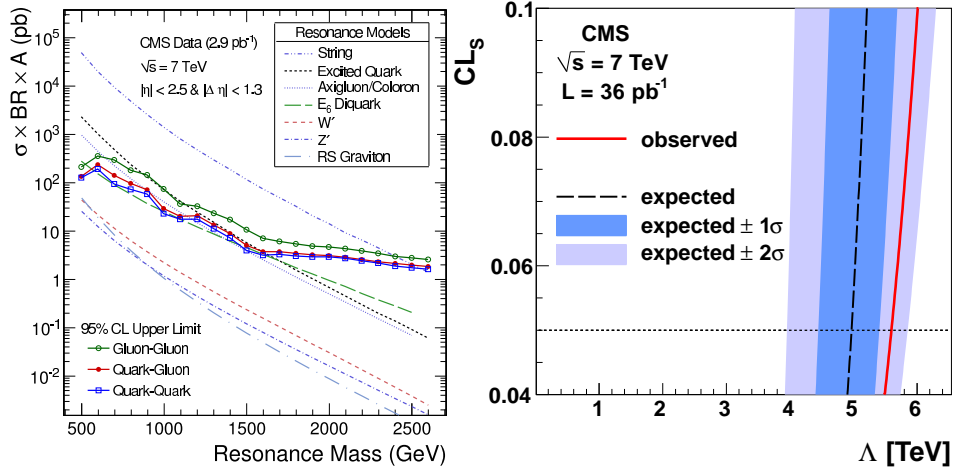


FIGURE 10. Left: upper limits on resonances in $g + g$, $q + g$ and $q + q$ scattering compared with the cross sections calculated in various scenarios, note in particular the limits on excited quarks and string resonances [51] (see also [50]). Right: limit on new contact interactions scaled by Λ , as obtained from a study of dijet angular distributions [52] (see also [53, 54]).

Composite quarks?

One of the first LHC results that set limits on physics beyond the Standard Model that are stronger than those set by previous experiments came from a search for excited quarks q^* that might have been manufactured in $q + g$ collisions and decay *via* $q^* \rightarrow q + g$ [50, 51]. As seen in the left panel of Fig. 10, these have now been excluded with masses up to 1.58 TeV, much stronger than the limit of 0.87 TeV set at the Tevatron collider.

String excitations?

In some string scenarios, the scattering of quarks and gluons in the channels $q + q$, $q + g$ and $g + g$ may reveal resonances at indistinguishable masses. The same LHC results shown in the left panel of Fig. 10 also exclude this possibility up to a mass of 2.5 TeV [51], a limit that is also much stronger than previous constraints.

Contact interactions?

Another possibility in composite models is that there may be new, non-renormalizable contact interactions of the form $\bar{q}q\bar{q}q$ and the like. These could show up *via* either deviations from the dijet invariant mass distributions calculated in QCD, or deviations from the expected angular distributions. The latter has also been used to set limits stronger than in previous experiments, as seen in the right panel of Fig. 10 [52] (see also [53, 54, 55]).

Microscopic black holes?

In some theories with large extra dimensions, gravity may become strong at the TeV scale, in which case the high-energy collisions of quarks and gluons might produce microscopic black holes [24]. The theories that predict such a possibility also predict that these microscopic black holes would decay very rapidly through Hawking radiation. (This has not averted some unfounded speculations that LHC collisions might produce stable black holes capable of eating up the Earth, speculations that are excluded by simple considerations of high-energy cosmic ray collisions on the Earth and elsewhere in the Universe [56].) The production and decay of microscopic black holes at the LHC has now been excluded over a large range of masses, as seen in Fig. 11 [57].

How else to probe string theory?

A remarkable recent theoretical development has been the realization that the AdS/CFT correspondence suggested by string theory could be used to calculate in simplified theories properties of the quark-gluon matter produced in relativistic heavy-ion collisions, starting with its viscosity [58]. Measurements of the viscosity of the medium produced in such collisions at RHIC have indicated that it is remarkably low [59], far lower than that of the superfluid Helium cooling the LHC magnets, and within a factor ~ 3 of the AdS/CFT lower limit. Early data from heavy-ion collisions seem to confirm the low viscosity of the quark-gluon medium [60], and also to provide remarkable evidence for large parton energy loss [61, 62]. Is it too much to hope for some quantitative tests of string ideas in heavy-ion collisions at the LHC?

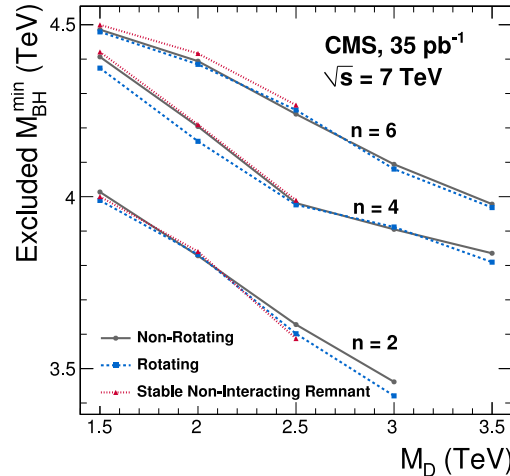


FIGURE 11. Excluded ranges of microscopic black hole masses under various assumptions about the number of extra dimensions n , the extra-dimensional Planck mass M_D , the angular momentum of the black hole and whether its decay leaves behind a (metastable) remnant [57].

A CONVERSATION WITH MRS. THATCHER

In 1982, just after the CERN $\bar{p}p$ collider started up, Mrs. Thatcher, the British Prime Minister at the time, came to visit CERN, and I was introduced to her as a theoretical physicist. “What exactly do you do?”, she asked in her inimitably intimidating manner. “I think of things for experimentalists to look for, and then I hope they find something different”, I responded. Somewhat predictably, Mrs. Thatcher asked “Wouldn’t it be better if they found what you predicted?” My response was that “If they found exactly what the theorists predicted, we would not be learning so much”. As it happened, the CERN $\bar{p}p$ collider found the W^\pm and Z^0 particles, as expected. Nevertheless, in much the same spirit as in 1982, I hope (and indeed expect) that the LHC will become most famous for discovering something NOT discussed in this talk!

ACKNOWLEDGMENTS

It is a pleasure to thank fellow members of the MasterCode Collaboration for sharing the fun, and the organizers for their kind invitation to speak at this interesting meeting.

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